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Fine Root Production and Soil Available Nutrients in Rubber Monoculture versus Rubber–*Flemingia macrophylla* Agroforestry

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Abstract: In the present study, we examined fine root production and soil available nutrients (N, P and K) across different soil depths in rubber monoculture and rubber–*Flemingia macrophylla* agroforestry of different stand ages. We used the ingrowth cores method and sampled 360 soil cores over four growth intervals, representing one year of growth for the present study. The results showed that root production and macronutrient concentrations generally decreased with increasing soil depth. Total fine root production was comparatively high in the youngest stand age (12 years) rubber monoculture; a similar trend was observed for the soil available P and K, but available N was greater in older than younger stand ages. Root growth and soil available P and K were all lower in the agroforestry system than the monoculture. Significant differences in fine root production with stand ages, management system and seasons suggest that fine root responses to the soil available nutrients are vital to understanding the precise response of above- and belowground biomass to environmental changes.

Keywords: agroforestry; fine roots production; nitrogen; phosphorus; potassium; vertical distribution; soil core; management types

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1. Introduction

The natural forest of southwestern China and much of continental southeast Asia has been extensively replaced with plantations of rubber trees (*Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg.) [1]. Replacement of natural forests by plantations can lead to the degradation of soil resources and ecosystem services with soil organic carbon (SOC) losses, accelerated soil acidification, changes in the quantity and composition of nutrient compounds, soil erosion and nutrient runoff, ultimately affecting land productivity, which threatens the future livelihoods of residents [2,3]. This has led to efforts to reduce the negative impacts of plantations on soil productivity and other ecosystem services [4,5]. Agroforestry has been proposed as one means to achieve resource sustainability in the rubber plantations of Xishuangbanna and continental southeast Asia [6,7]. It is critical to know whether agroforestry promotes greater soil resource conservation, productivity and thus ecosystem service sustainability. One means of evaluating these properties is to consider fine root productivity and its spatiotemporal impacts on soil fertility in systems of rubber monoculture versus rubber agroforestry.

Fine roots are most commonly defined as plant roots that are two millimeters or less in diameter whose primary function is the acquisition and transport of soil resources (e.g., nutrients, water) [8]. Fine roots collectively comprise most of the total length of the root system of a plant [9]. As fine roots age, their function shifts from acquiring soil resources to transporting materials to other plant parts [10,11], and are closely related to the forest stand type, as well as topographic and edaphic factors, depending on the dominant tree species [12–14]. They are the dynamic part of the root system, having a relatively short lifespan with rapid turnover. Upon death, these fine roots contribute significant amounts of carbon and nutrients in adjoining soil [13,15]. It has been reported that 18% to 58% of the total soil N in soil is added by the mortality of fine roots [16–18]. Growth and turnover of fine roots account for about 33% of global net primary production and for 3–30% of the total root biomass in terrestrial ecosystems, consequently providing the basis for understanding belowground competition among species [19,20].

Several understory plants are grown in agroforestry systems with rubber, including crop plants such as tea (*Camellia sinensis* L.) and several ginger species (Zingiberaceae) [21], and also nitrogen-fixating legumes aimed at enriching the soil quality and thereby productivity of the rubber plantations [22,23]. Our investigations are focused on Flemingia macrophylla (Willd.) Kuntze ex Merr., an excellent understory cover crop. The species grows profusely with moderate drought tolerance and significantly contributes to soil organic matter accumulation and resists occasional flooding. It is often intercropped with rubber for improving biomass, weed control, erosion, decreasing soil temperature, conserving moisture and acting as a windbreak, and can promote the growth of rubber trees based on fine root growth, stem and leaf biomass [24,25]. Previous research has concluded that Rubber-*Flemingia* agroforestry enhances the storage of carbon, increases soil nitrogen content and nutrient accumulation and conserves water and soil [26,27]. However, it is unclear how including *Flemingia macrophylla* as a cover crop alters fine root production or the vertical spatial arrangement of fine root growth. Evaluating these patterns could help us to understand whether there are differences in how plantation trees use soil resources in vertical space when grown as monocultures versus being grown in agroforest systems.

Several studies have demonstrated that fine root biomass decreases with depth in the soil profile [28–31]. Plants can obtain nutrients as soon as organically bound nutrients from the litterfall are mineralized or even directly from the decaying material through interactions with mycorrhizas and the exudation of extra-cellular compounds [32,33]. Therefore, most of the roots are located in the top 10 cm layer as an adaptation to maximize nutrient uptake. However, some studies observed that fine root production increases with soil depth, suggesting that growing into deeper soil layers is an additional strategy to satisfy the requirement for more resources in support of greater above- and belowground productivity in species mixtures in mature stands [34,35]. In addition, some studies have indicated that root growth increases in deeper soil layers during the dry season to absorb water in those layers [36,37]. These contrasting results indicate that root growth across depths is context-specific and seasonally specific, and thus may be important to understand differences in root production in monocultures versus agroforestry systems.

Fine root production is highly affected by the stand age of plantations. The effects of stand age on fine root production remain poorly understood. Several studies have shown an increasing trend of soil N concentration with stand age [38,39], but other studies of secondary forest ecosystems have noted that carbon sequestration decreases with age [40–42], suggesting that forests and plantations may become less productive over time, potentially due to soil nutrient depletion [43]. Thus, it is unclear how stand age might affect fine root production and whether there is an interaction between stand age and soil depth at which root growth occurs, nor is it understood how the inclusion of *Flemingia* alters these spatiotemporal dynamics.

We examined changes to fine root production and available soil macronutrient concentration (N, P, K) at different soil depths over one year of growth in rubber stands of different ages that were either monocultures or agroforests intercropped with *Flemingia macrophylla*. The objectives of this study were:

(i) To compare vertical fine root production and soil available nutrients (N, P, K) in rubber monoculture versus rubber–*Flemingia* agroforestry systems with different-aged rubber stands (12, 15, and 24 years).

(ii) To evaluate the seasonal variations in fine root production and soil available nutrients.

(iii) To evaluate the correlation between fine root production and available nutrient concentrations in rubber monoculture versus rubber–*Flemingia* agroforestry systems.

2. Materials and Methods

2.1. Site Description

The experiment was performed in Mengla County, Xishuangbanna Prefecture, Yunnan Province (21°33′ N, 101°28′ E), southwest China. The area has a tropical monsoonal climate, with a wet season between May and October and a dry season from November to April. The annual average rainfall is ~1500 mm, with more than 85% falling in the wet season [44]. The mean annual temperature is ~21.5 °C, with a mean maximum monthly temperature of 26.5 °C in June and a mean minimum monthly temperature of 17.1 °C in December. The soils are classified as oxisols with a pH of about 5.0, approximately 2 m deep overlying arenaceous shale sediments [45].

2.2. Experimental Design

The study site was composed of rubber monocultures planted in 1994, 2003 and 2006, meaning the stand ages were 24, 15 and 12 years, respectively, when the experiment was conducted (2018). The rubber trees were planted in a conventional 2.5 m × 8 m spacing arrangement, with each stand covering 1 ha (10,000 m^2). In June 2010 (8 years prior to the start of this experiment), each age stand was divided into 6 subplots of 25 m × 20 m (500 m^2), in which three were underplanted with *Flemingia macrophylla* (rubber–*Flemingia* agroforestry) and three were not (rubber monoculture). *Flemingia macrophylla* were interplanted into each stand at a density of 0.8 m × 1.0 m inter-row spacing [46]. Subsequently, all subplots were managed similarly, except *Flemingia* was clipped to approximately 30 cm above the ground in December each year and the cut material was left on the ground

In March 2018, root ingrowth soil cores were established in each of the six subplots in each stand age. The cores were made with a sharp stainless steel soil drill with a 9 cm inner diameter. Cores were dug from 0 to 60 cm below ground level. All roots in the soil were carefully removed by hand, and the rootless soil was put back into the cores and compressed to ground level. We installed 20 soil cores (5 rows × 4 columns) in each subplot. For all three ages, a total of 360 soil ingrowth cores (3 ages × 6 subplots × 20 cores) were installed. The cores were covered with leaf litter and marked with steel rods.

2.3. Estimation of Fine Root Production

Fine root production was estimated through the ingrowth cores method [47–49]. We measured one year of fine root production with 4 sampling dates spread apart by 3-month intervals, yielding 4 periods of growth, i.e., S1 (June 2018), S2 (September 2018), S3 (December 2018) and S4 (March 2019). S1 and S2 samples represent wet season samples and S3 and S4 represent dry season samples. Five cores were recovered from each subplot at each sampling date (total = 90 ingrowth cores across subplots per sampling date).

After removal, the ingrowth cores were carefully divided into 0–10, 10–20, 20–30, 30–40, 40–50 and 50–60 cm depths. The 5 soil core samples for each soil layer per sampling date were combined together into a single plastic bag, yielding 6 combined samples per subplot per sampling date (6 depths × 6 subplots × 3 ages = 108 samples per date × 4 dates = 432 total samples). Soil samples were placed on a 1 mm sieve and floated in the water tub several times to separate roots from soil residues. Both components were used for subsequent analyses.

The roots were handpicked with forceps from the sieve, and roots with diameter > 2 mm were determined and discarded. The sorted fine roots from all depths were then oven-dried at 70 °C for 48 h to obtain a constant mass, using an electronic balance, and we calculated the biomass in Mg h^{-1} per 10 cm layer, using the inner radius of the auger:

$$\mathrm{Pfr} = (\mathrm{Wfr} \times 100)/(\pi \times (\mathrm{ric})^2$$

where Pfr is the production of fine roots (Mg per ha), Wfr is the dry weight of fine roots (g) and ric is the radius of the ingrowth core (4.5 cm).

2.4. Soil Chemistry Analysis

Soil residues from the ingrowth cores were used for soil chemistry analyses, in order to link fine root properties with soil chemistry. The soil was dried at 105 °C to constant weight for at least 24 h, then sieved through a sifter with a 0.2 mm mesh size and stored in plastic bags for each layer for each core for available N, P and K analysis. Soil available N was measured by extracting in 2 mol L^{-1} KCl and quantified using a continuous flow auto-analyzer (SEAL Analytical GmbH, Germany) [50]. Soil available P was measured using 0.03 mol L^{-1} of NH4F and 0.025 mol L^{-1} of HC1 and then analyzed colorimetrically [51], and available K was analyzed through an inductively coupled plasma atomic emission spectrometer ((ICP-AES, iCAP6300, Thermo Fisher Scientific, Waltham, MA, USA) followed by digestion in nitric–perchloric acid solution [52].

2.5. Data Analysis

All analysis was performed in statistical R software version 4.1.0 (R Core Team, 2021; R Foundation for Statistical Computing: Vienna, Austria) [53]. We calculated fine root production in each soil layer of each ingrowth core as the average dry mass of live plus dead fine roots of each ingrowth core. Estimates of fine root production were calculated by determining differences in dry mass for all sampling intervals. Prior to further analysis, we used the Shapiro–Wilk test for data normality and log-transformed data as necessary to improve the normality of the data.

First, we used linear mixed effect models (using the 'lme4' package) to test whether fine root production and soil nutrients (available N, P, K) differed by management type (rubber monoculture versus rubber–*Flemingia* intercropping), soil depth (6 classes: 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, 40–50 cm, 50–60 cm) and season (4 periods: 0–3 months, 3–6 months, 6–9 months, 9–12 months). Subplot name (18) was included as a random effect since multiple cores were collected from each subplot over time. We used the lmer function of 'lme4' package [54] to run the mixed model analysis.

Second, we used Pearson's correlation to test for covariation strength among fine root production and available nutrients (N, P, K). For this analysis, we considered only the fourth sampling period, on the assumption that cumulative root growth would be greatest over the full growing season. We also summed values across depths understanding that root mass likely decreased exponentially with soil depth. Thus, we had 18 sampling units (6 age × management combinations × 3 replicates). We then split the data between management types to understand whether relationships between fine root mass and soil nutrients differed by management type.

3. Results

3.1. Impact of Depth, Season and Stand Age on Fine Root Production

Substantial variation in fine root biomass was due to differences across soil depths (see sums-of-squares in Table 1), reflecting the natural change in root biomass from high values in shallower layers to low values in deeper layers (Figure 1). The sampling interval also explained substantial variation (Table 1), with large differences in biomass accumulation between the first three intervals (mostly positive) and the last interval (mostly negative), likely reflecting ambient growing conditions (the fourth sampling period occurred during the late dry season), but these responses were not universal. The highest significant interaction for fine root biomass was I × M × A, indicating a significant interaction between sampling interval (I), management type (M) and age (A) of the plantation stand. The major differences were as follows: rubber monoculture stands had greater root biomass than the rubber–*Flemingia* intercropping stands. Younger age stands showed persistent biomass accumulation into the fourth sampling interval, whereas older stands had more noticeable declines in root biomass during the same period, suggesting substantial dieback for older stands than younger stands during the dry season. Fine root biomass accumulation across all soil layers was noticeably greater in the youngest monoculture stand than other stands (Figure 1).

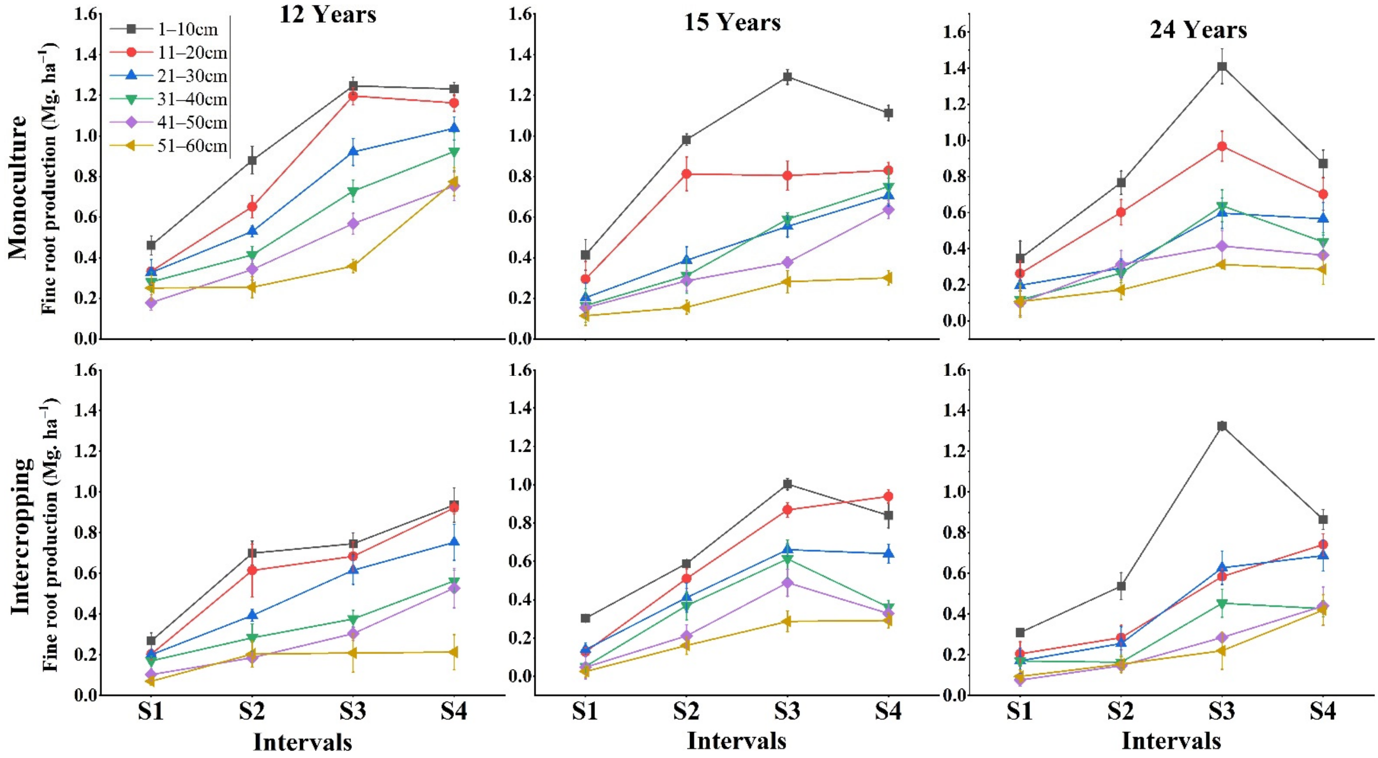

Figure 1. Fine root production in different soil layers across four sampling intervals (S1, June 2018; S2, September 2018; S3, December 2018; S4, March 2019) within different-aged stands of two plantation management types (rubber monoculture versus rubber–F. macrophylla intercropping).

3.2. Impact of Depth, Season and Stand Age on Soil Available Nutrients

Soil available nutrients were similarly responsive to soil depth and sampling intervals (Table 1, Figures 2–4), although the explanatory power of sampling interval was much lower than for fine root mass. The highest order significant interaction for available N and K was I × M × A, similarly to fine root mass. Although the interaction was significant for available N, the magnitude of the differences between management × stand age combinations for available N were visually small, with rather similar total nutrients in each soil layer and a steady decline in available N with increasing soil depth (Figure 2). Old stands showed a notable decline in soil N in the last sampling period, similar to fine root biomass.

Table 1. Summarized ANOVA for linear mixed effect models testing whether stand age, sampling interval, soil depth, management system (rubber monoculture versus rubber–*Flemingia* intercropping) or their interactions significantly impact fine root production and available N, P or K. Effects significant at $p < 0.05$ are emboldened.

Effects			**Fine Root Production (Mg ha^{-1})**			**Available Nitrogen (mg kg^{-1})**			**Available Phosphorus (mg kg^{-1})**			**Available Potassium (mg kg^{-1})**		
Fixed Effect	**df**	**Error df**	***SS*q**	***F***	***p***	***SS*q**	***F***	***p***	***SS*q**	***F***	***p***	***SS*q**	***F***	***p***
Age (A)	2	0	0.42	1.11	1.000	0.07	1.43	1.000	1.74	1.94	0.146	0.02	0.21	1.000
Intervals (I)	3	276	**127.18**	**221.18**	**0.001**	**0.41**	**5.62**	**0.001**	**10.88**	**8.07**	**0.001**	**0.56**	**4.31**	**0.005**
Managements (M)	1	0	0.95	4.96	1.000	0.00	0.02	1.000	0.60	1.34	0.248	0.05	1.19	1.000
Depths (D)	5	276	**88.06**	**91.89**	**0.001**	**26.35**	**215.84**	**0.000**	**89.38**	**39.76**	**0.001**	**4.91**	**22.84**	**0.001**
I × M	3	276	1.16	2.01	0.112	**0.25**	**3.44**	**0.017**	**13.00**	**9.64**	**0.001**	**0.46**	**3.56**	**0.015**
I × A	6	276	**5.11**	**4.44**	**0.001**	**1.15**	**7.85**	**0.000**	**30.21**	**11.20**	**0.001**	**0.52**	**2.03**	**0.062**
M × A	2	0	0.20	0.53	1.000	0.02	0.46	1.000	1.23	1.37	0.256	0.03	0.38	1.000
I × M × A	6	276	**5.09**	**4.42**	**0.001**	**0.74**	**5.05**	**0.000**	**17.23**	**6.39**	**0.001**	**0.95**	**3.68**	**0.002**
A × D	10	276	2.17	1.13	0.337	0.34	1.41	0.175	**16.36**	**3.64**	**0.001**	0.53	1.24	0.267
M × D	5	276	0.93	0.97	0.437	0.12	0.96	0.445	1.39	0.62	0.686	0.13	0.59	0.707
I × D	15	276	2.79	0.97	0.486	0.18	0.50	0.937	4.75	0.70	0.779	0.27	0.42	0.973
I × M × D	15	276	2.04	0.71	0.775	0.20	0.55	0.912	4.24	0.63	0.851	0.08	0.13	1.000
I × A × D	30	276	3.78	0.66	0.917	0.18	0.24	1.000	6.33	0.47	0.993	0.40	0.31	1.000
M × A × D	10	276	2.21	1.16	0.321	0.26	1.08	0.377	**13.98**	**3.11**	**0.001**	0.37	0.86	0.574
I × M × A × D	30	276	2.87	0.50	0.988	0.19	0.25	1.000	6.58	0.49	0.990	0.33	0.26	1.000
Variation explained														
R^{2}m				74			0.77			0.85			0.64	
R^{2}c				77			0.79			0.89			0.77	

Notes: Significant effects are shown in boldface as follows: $p \leq 0.001$, $p \leq 0.01$, $p \leq 0.05$.

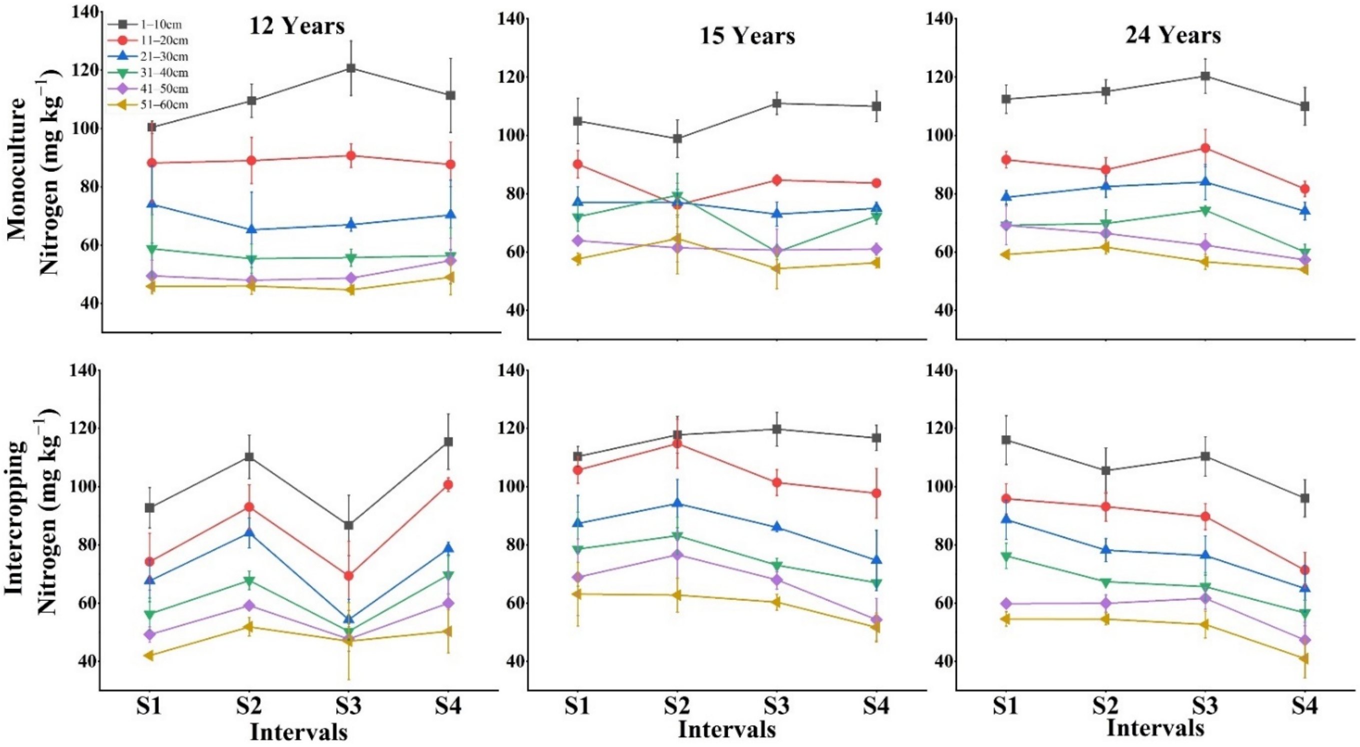

Figure 2. Soil available N in different soil layers across four sampling intervals (S1, June 2018; S2, September 2018; S3, December 2018; S4, March 2019) within different-aged stands of two plantation management types (rubber monoculture versus rubber–F. macrophylla intercropping).

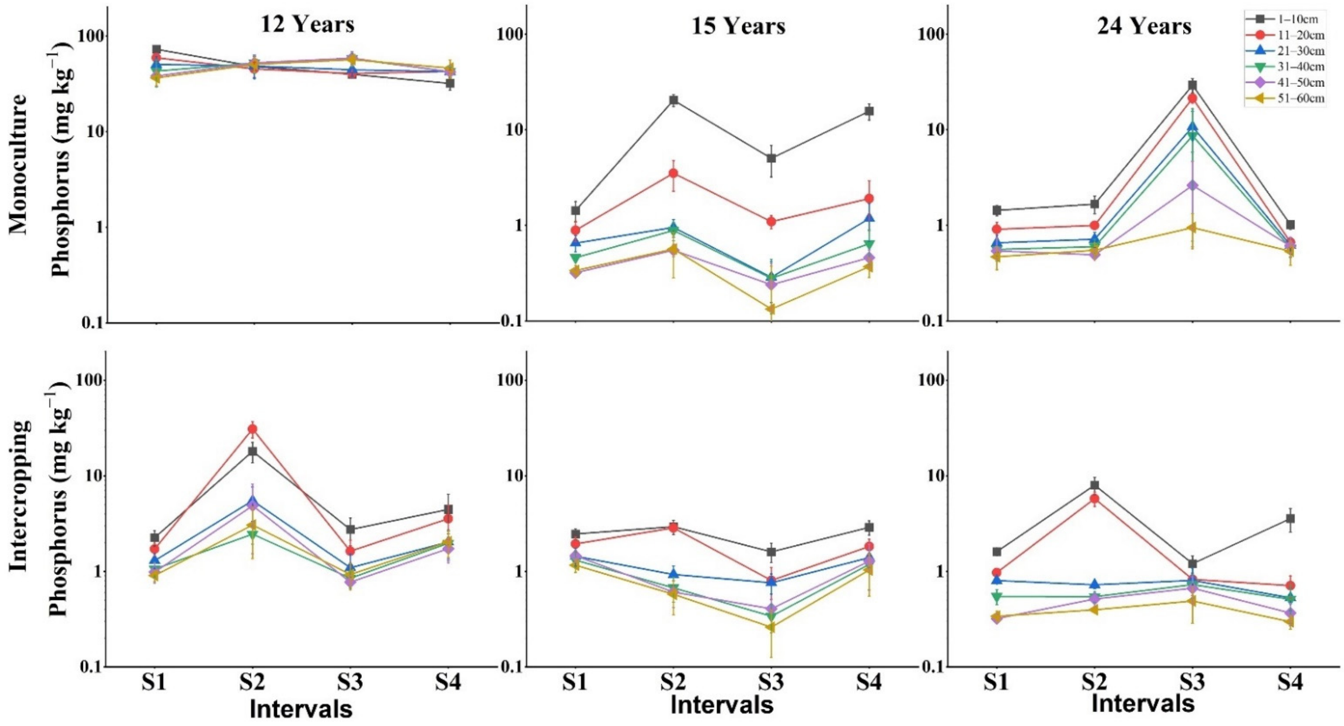

Figure 3. Soil available P in different soil layers across four sampling intervals (S1, June 2018; S2, September 2018; S3, December 2018; S4, March 2019) within different-aged stands of two plantation management types (rubber monoculture versus rubber–F. macrophylla intercropping).

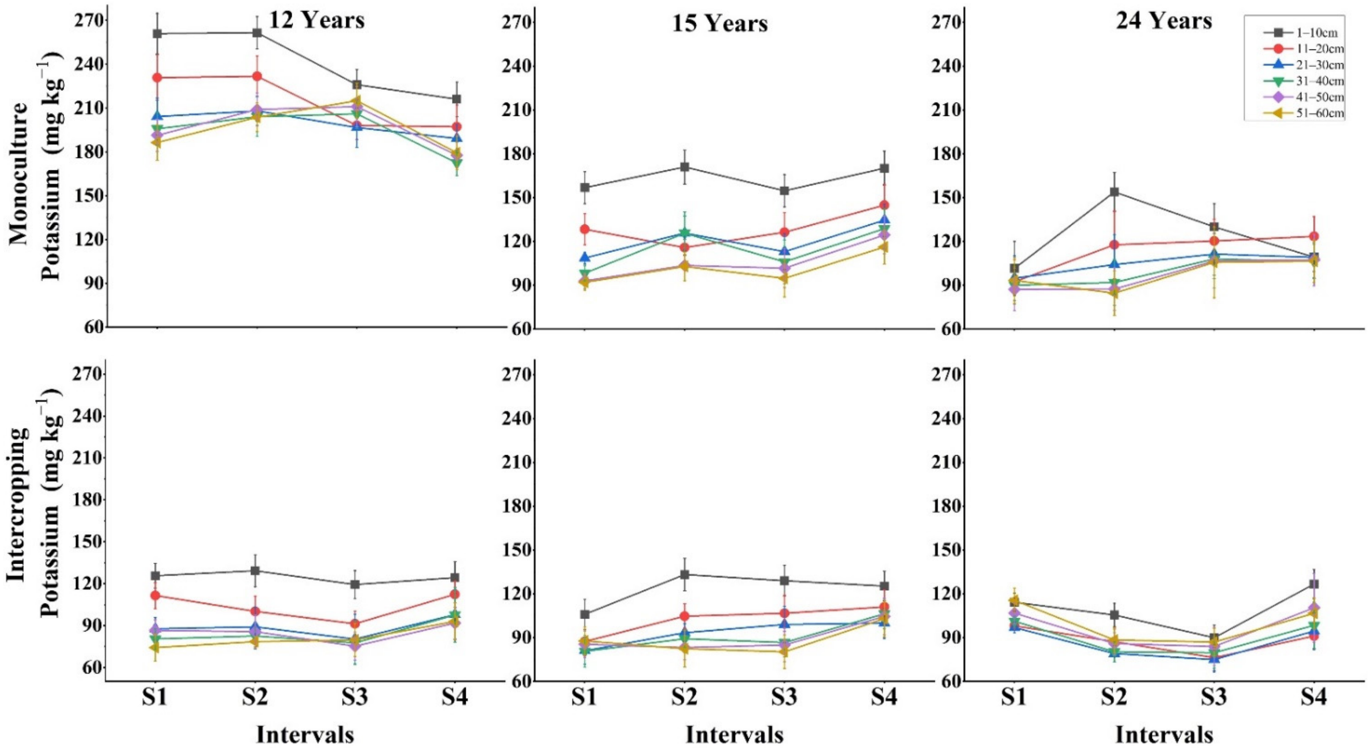

Figure 4. Soil available K in different soil layers across four sampling intervals (S1, June 2018; S2, September 2018; S3, December 2018; S4, March 2019) within different-aged stands of two plantation management types (rubber monoculture versus rubber–F. macrophylla intercropping).

Soil available K was greater in monoculture stands than intercropping stands, and was greatest in the youngest monoculture stand (Figure 4). In that stand, there was an obvious decline in available K after the second interval, which was mostly not apparent in the remaining stands. Available potassium in the 12-year and 15-year intercropping stands did not differ substantively.

Available phosphorus included two three-way interactions: I × M × A and M × A × D, indicating that independently of sampling interval, soil available phosphorus differed between soil depths differently across management type and stand ages. Consideration of the data (Figure 3) indicates that the interactive effect was related to substantial differences in soil available P in the youngest stand monoculture, which had much greater available P than any other age × management type. Concentrations of available P in different soil layers also did not follow consistent declines with depth in this 12-year-old monoculture stand when compared to other age × management types. The other noticeable pattern was that available P was highest in the second sampling interval for the 12-year intercropping stand and highest in the third sampling interval for the 24-year monoculture stand. In general, available phosphorus was greater in the rubber monoculture stands than the intercropping stands.

3.3. Correlations between Fine Root Mass Production and Soil Nutrients across Management Types

In rubber monoculture stands, fine root mass was positively correlated with available P and available K but uncorrelated with available N (Figure 5). By contrast, in rubber–*Flemingia* intercropping stands, fine root mass was significantly negatively correlated with available N, P and K. In both management types, available P was positively correlated with available K, but available N was weakly correlated with available P and uncorrelated with available K.

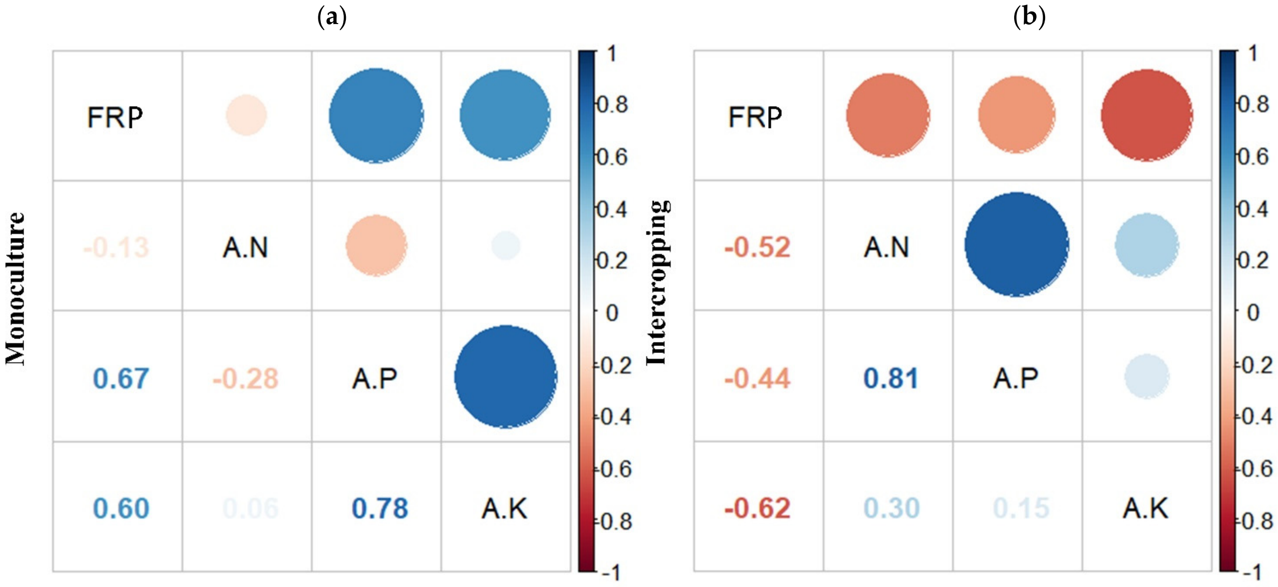

Figure 5. Pearson correlation matrices of fine root production (FRP), soil available nitrogen (A.N), soil available phosphorus (A.P) and soil available potassium (A.K) under two management systems: (**a**) rubber monoculture and (**b**) rubber–*Flemingia* intercropping. The significance levels for correlations are $p < 0.001$, $p < 0.01$ and $p < 0.05$. All variables were normalized prior to correlation testing.

4. Discussion

In this study, we evaluated how fine root biomass and soil available macronutrients (N, P, K) changed across soil depths and growing periods over a full year in rubber monocultures versus rubber–*Flemingia* intercropping agroforestry systems, across rubber stands of different ages. For most response variables, patterns of change with soil depth followed standard expectations, i.e., decreasing root production and nutrients with depth profile [28,30], with only available P showing a response to different management and ages across soil depth, but this unusual pattern was only observed in the 12-year monoculture treatment (Figure 3). In that treatment combination, soil available P was greatest in the upper soil layers in the early sampling periods, but in later periods, lower soil layers had greater available P. The combined evidence suggests that adding *Flemingia* into rubber reduced total final root production and reduced soil available P and K.

4.1. Management Type Effects on Fine Root Production and Soil Nutrients

The rubber–*Flemingia* agroforestry system did not enhance total fine root production in rubber stands in our study, but rather reduced it relative to rubber monocultures. Likewise, the findings of Jacob et al. [55] have also shown no positive effect of stand diversity on the standing fine root growth. Contrastingly, Brassard et al. [56] and Domisch et al. [57] found that fine root productivity was higher in mixed than single-species stands. Sun et al. [58] have suggested contrasting responses associated with differences in climatic conditions; site fertility and species identity may determine these contrasting observations. Archambault et al. [59] suggest that the aboveground positive diversity effect may be due to increased efficiency of resource extraction, resulting in less allocation towards fine roots with increasing diversity. In our study, less fine root production in agroforestry might be explained by more effective soil resource uptake of fine root production in the community over the previous years: *Flemingia* was planted in 2010, eight years before our sampling took place. Moreover, *Flemingia* is an N-fixing legume, a function that has very high requirements for P and K [46], and thus may have severely depleted soil P through extraction in the preceding years, causing the lower P and K values in the intercropping stands than the monoculture stands (Figures 3 and 4). This is also supported by the strong negative correlation between root mass and soil available P and K (Figure 5). This can only be fully resolved by following soil nutrient use over several years directly from the time of planting of *Flemingia* into the plantations, which, unfortunately, we were unable to do. Soil nitrogen did not seem to respond very strongly to differences in plantation type (although there were significant interactions—Table 1), and also showed a negative correlation with fine root mass in both the rubber monoculture and rubber–*Flemingia* intercropping stands (Figure 5), suggesting that root biomass was not strongly affected by the management type. This is somewhat surprising, since *Flemingia* has been chosen as a support crop because it is thought to enhance to soil fertility through N fixation. The loss of P and K in the soils may render *Flemingia* useless as a N-enriching crop, but perhaps the benefits are expressed in aboveground rubber production, which we did not consider here. In the present study, rapid decomposition of leaf litter boosted by high moisture and temperatures in the tropical environment might ensure rapid uptake of available nutrients into aboveground biomass [60,61]. If not, then the benefits of *Flemingia* as a cover crop in rubber plantations may need re-evaluation. A possible explanation for the loss of soil P and K is that cutting *Flemingia* down in December each year is actually problematic. December is during the early dry season in Xishuangbanna (our third sampling period), and *Flemingia* plants are still green at the time of cutting, which may lead to loss of nutrients because the plants do not dieback naturally, during which time they would withdraw a large amount of nutrients from their leaves into belowground structures [62]. At the same time, cutting plant material during the early dry season prevents this cut material from being decomposed because of the combination of low water availability and low temperatures. It would be useful to investigate whether delaying cutting to the late dry season changes the depletion of soil nutrients over time.

4.2. Stand Age Effects on Fine Root Production and Available Soil Nutrients

We observed some differences in fine root growth over time across ages (Figure 1). Generally, root biomass increased across all sampling periods in the youngest stands, but the oldest stands showed a marked decline in root biomass in the final period. Our only explanation for this is that the lower soil fertility (available P, available K) of the oldest stands may compromise the ability of rubber plants to sustain root biomass through the late dry season. While we found marked declines in available soil P and K with increasing stand age, we did not find marked trends in available N across rubber stand ages. This contrasts with other studies which found increasing soil N concentrations with stand age [38,39]. That we did not find this pattern likely reflects the fact that N is more labile, being extracted from atmospheric resources. On the other hand, the greater demand for growth and latex production and no input of fertilizers lower the content of P and K in a mature mix plantation, which could be attributed to a large amount of P loss from consecutive latex removal of mature rubber trees, along with nutrient loss via runoff and erosion over time.

Soil available K is mostly leached by runoff easily; hence, the amount that is accessible to the fine roots is hardly lower than N or P, despite occasionally being higher than N and especially P [63]. The results suggest that total P and K will become increasingly depleted with plantation age, and thus, fertilization with P and K may be necessary to maintain the productivity of older rubber stands [43]. Furthermore, in the present study, we found that N and K were significantly higher in the top mineral layer and decreased with soil depths (Figure 4). However, P did not decrease in the lower soil depths (30–60 cm), probably due to plants' slower root respiration and absorption, especially when N-fixing species were cut down and covered in situ [46]. Lower soil depths do not have access to high quantities of nutrients released by litterfall decomposition as in the surface layers. This can probably be attributed to the constant deposition of root residues in these systems and the smaller mineralization of P [64].

5. Conclusions

The results of this study demonstrate that fine root production and soil nutrients (N, P, K) significantly vary with stand age, growing seasons, soil depths and management practices. Rubber monoculture produces greater fine roots than agroforestry, and thus exhibits better soil nutrients. However, decreased soil nutrients and fine roots in the agroforestry system would possibly be because of the problem with cutting management of *Flemingia macrophylla* in previous years that might have exported the organic matter from the site. Fine root production and most available nutrients decreased with soil depth in all the plantations studied. However, available P increased with the increase in soil depths in the youngest rubber monoculture, showing the weathering addition of P. Our results offer an understanding of the dynamic spatiotemporal relationship between fine roots and nutrients in rubber monocultures versus rubber–*Flemingia macrophylla* agroforestry systems.

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